Amending Numerical Weather Prediction forecasts using GPS Integrated Water Vapour: a case study

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Abstract. With GPS independent observations of humidity can be made. The data quality has shown to be very good and the high temporal resolution can be of great value for forecasters. GPS Integrated Water Vapour (IWV) can be used to validate the amounts of humidity in Numerical Weather Prediction (NWP) model forecasts. This paper presents a case in which the operational limited area model at KNMI (as well as the global model of ECMWF) strongly underestimated the diurnal temperature cycle. The humidity in the boundary layer of the model triggered evaporation, which affected the temperature forecast. Goal of this paper is to show the additional information of GPS IWV for NWP models and discuss the benefit and use of the GPS IWV observations for amending the operational forecast.

1. Introduction

Forecasters nowadays use a lot of different sources of information. Satellite images and Numerical Weather Prediction (NWP) models are used together with the synoptic surface and radiosonde observations. All this information is combined to obtain a good diagnosis of the actual state of the atmosphere.
Water vapour is one of the parameters that is highly underestimated in the current synoptic weather observation systems due to lack of upper air humidity observations. It is, however, of major importance that this parameter is estimated more or less correctly. For example severe weather events, such as thunderstorms can be triggered through an excess of humid air. Moreover, good cloud forecast depend highly accurate values of the humidity.
Integrated Water Vapour (IWV) derived from Global Positioning Systems (GPS) may help to improve the diagnosis of the actual state of the atmosphere and thus may lead to better forecasts.
Signals from GPS are widely used to obtain very accurate location parameters. A GPS signal from one of the GPS satellites to a receiver is delayed by a certain amount depending on, amongst others, the total amount of water vapour along the signal path. This delay along the path is called slant delay. By processing all observed slant delays within a certain time window errors and unknowns, such as satellite or receiver clock errors can be estimated. An estimate of the Zenith Total Delay (ZTD) for any GPS receiver is determined simultaneously. The Zenith Wet Delay (ZWD) can be computed from the signal by differencing the ZTD with the zenith 'dry' or hydrostatic delay (ZHD),

$$ZWD = ZTD - ZHD.$$

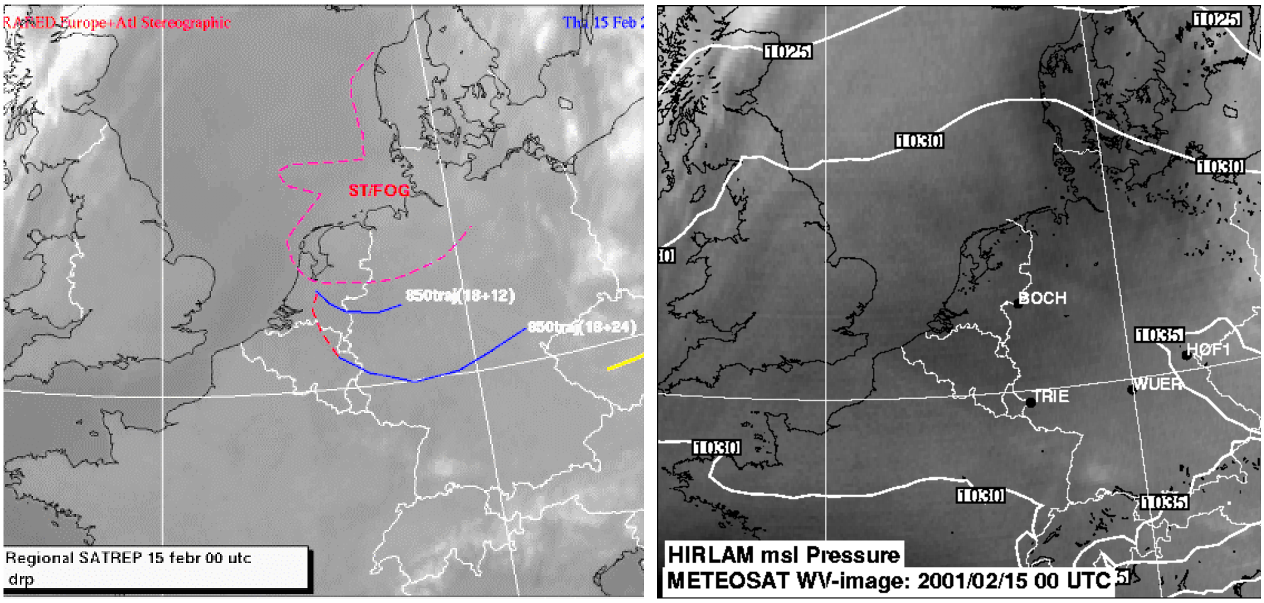
The ZHD can be approximated using the surface pressure [Saastamoinen, 1972], while the ZWD is associated with the vertically integrated column of water vapour overlying the GPS receiver

$$IWV = 1/k \; ZWD,$$

where k depends on the weighted mean temperature of the atmosphere, which in turn can be approximated as a function of the surface temperature [Bevis, 1994].
The network used in this paper takes part in the Near Real Time Campaign of the European COST716 action. Data from this campaign are available from the beginning of February 2001. The campaign consists of 6 (overlapping) networks each processed by a different processing center. The networks currently cover large parts of Europe. One of the goals of this was to deliver the ZTD estimates to the meteorological community within 1h and 45min and with acceptable accuracy. The data used in this paper meet these criteria.
In this paper, a case is presented for which the operational Numerical Weather Prediction Model (NWP) HIRLAM (HIgh Resolution Limited Area Model) underestimated the 2-meter temperature. In Section 2 the weather situation is described. Section 3 contains the discussion of the forecasting problem. Section 4 discusses the GPS IWV values as observed by the Near Real Time Network from COST716 processed by GFZ, Potsdam. The last section contains the conclusions.

2. Weather situation

The weather situation on 15 February 2001 at 00utc was governed by a high-pressure system covering a large part of Western Europe. In Figure 1(a) a regional SATREP (Satellite Report) [ZAMG, KNMI, FMI, 2000] is shown. This figure shows the METEOSAT infrared image, with some clouds over Scotland and the German-Polish border. An easterly flow transported air from mid Germany to the Netherlands. Trajectories of air masses as derived from NWP show that on 15 February at 06utc the air mass over De Bilt originates from mid-west Germany and is subsiding along the trajectory (indicated by the short blue line in Fig. 1(a)). The air in the late afternoon on 15 February has its origin in the eastern part of Germany near the Czech border. The air mass sinks during the first part of the trajectory (blue line), while over Belgium (at approximately 12utc on 15 February) the air mass starts rising and continues to rise during the last part of its trajectory. The red dashed line indicates this.
The high-pressure system together with the METEOSAT water vapour image is shown in Fig. 1(b). The dark colour indicates a relatively dry upper troposphere.



(a) (b)

Figure 1. (a) Regional SATREP operationally created at KNMI valid for 15 February 2001 00utc. Background is the METEOSAT infrared image as disseminated by EUMETSAT. The two lines indicate trajectories of air masses at the 850hPA level for different forecast length derived from HIRLAM (respectively 12 hours and 24 hours). The colour of the line indicates whether the air mass is rising (red dashed) or subsiding (blue). (b) METEOSAT water vapour image together with the mean sea level isobars from HIRLAM. Also shown are the GPS sites close to the trajectories shown in (a).

3. Forecasting problem

The forecasted 2-meter temperature showed a large difference with respect to the observed 2-meter temperature in De Bilt. The maximum of the first was around 8-9 ^{o}C, while the latter had a maximum of around 13-14 ^{o}C. The NWP model HIRLAM is known to underestimate the 2-meter temperature. However, even a statistical correction algorithm did not indicate the large diurnal cycle as is shown in Fig. 2. The model had large problems to reproduce the increase in temperature around noon. A forecaster without any other information would not be able to estimate the observed maximum 2-meter temperature.

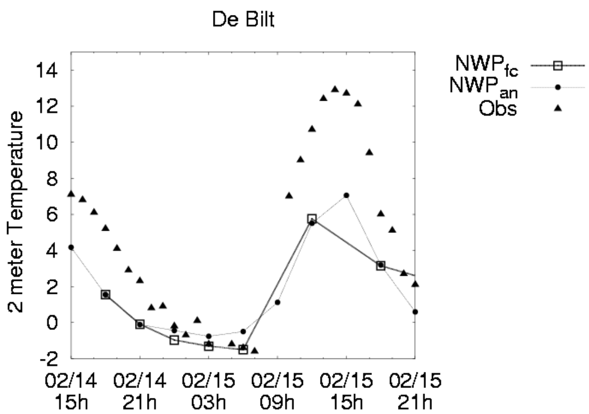


Figure 2. Observed, analysed and forecasted 2-meter temperature in De Bilt.

Currently, research is carried out to improve the 2-meter temperature forecast quality. The case presented here is too extreme to be cured by a better algorithm to calculate the 2-meter temperature from a model field.

4. Time series of IWV along the trajectories

For both trajectories the GPS IWV is compared to IWV derived from NWP forecast (abbreviated as NWP-fc) and NWP analysis (abbreviated as NWP-an). Each analysis can be regarded as the best representation of the state of the atmosphere with respect to the model resolution. Surface wind and pressure observations together with radiosonde observations form the backbone of the analysis. The currently used analysis of the NWP model does not assimilate GPS IWV or ZTD observations. The analysis scheme used for the operational NWP model at KNMI is optimal interpolation scheme. A model forecast is based on an analysis and calculates from this the state of the atmosphere at a future time. This calculation is based on fluid and thermodynamics physics laws.
Every three hours an analysis is made and archived at KNMI and every 6 hours a forecast is archived. This forecast contains model fields at a 3 hour interval for the first 12 hours and every 6 hours for forecast length from 12 to 48 hours. A three hour forecast valid on 14 February 21utc is denoted as 14 February 18utc +03.
The GPS-sites close to the trajectories used in this comparison are shown in Fig. 1(b). These sites reported IWV values in near real time on 14 and 15 February.

4.1 Trajectory +12

This trajectory starts in the middle west of Germany and the air mass reaches De Bilt on 15 February 06utc. The GPS site Bochum (abbreviated as BOCH in Fig. 1(b)) lies very close to this trajectory and the air mass passes Bochum at approximately 00utc on February 15. The data sets shown in Fig. 3 are GPS IWV values, forecasted

IWV values from a NWP run which started on 14 February 18utc and the NWP IWV analysis values.

The time series of the NWP derived IWV and GPS IWV at the GPS receiver location show a discrepancy, see Fig. 3. The reason for this may lie in the difference in height determination for the model and the GPS receiver. Moreover, the horizontal resolution of the model used here is around 50km. When the GPS receiver is situated on a small hill, which is not in the orography of the model, deviations or biases are introduced. However both GPS and NWP derived IWV estimates show the same (almost diurnal) trend.

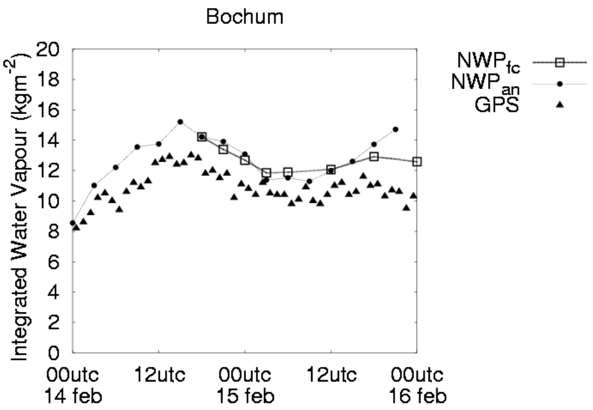


Figure 3. Time series of IWV derived from NWP analysis and forecasts together with GPS derived IWV

Another way to show that the IWV behaviour for Bochum is consistent for all three time series, the deviation from a mean value is calculated. This mean IWV value, which is determined for each of the three time series separately, is the mean of the observed IWV values at the forecast times, that is at 14 February 18utc +00h, +03h, +06h, +09h, +12h, +18h, and +24. This mean will be called "mean at forecast time". Note that the time frequency of the forecast implies that the means values for the other two data sets are calculated from a subset of these data sets. Using this mean at forecast time for a certain location the biases introduced by errors in height or model resolution are diminished. These offsets (denoted as ΔIWV) for all three time series show indeed more or less the same signal, see Fig. 4. Note that the GPS signal is noisier than the NWP signal.

The fact that all three signals are more or less the same indicates that the change in amount of integrated water vapour in the model analysis and forecast is in agreement with the changes observed by GPS IWV.

4.2 Trajectory +24

The forecast length of this trajectory is 24 hours. Nearby GPS sites of this trajectory are Hof (abbreviated as HOF1), Wurzburg (WUER) and Trier (TRIE), see Fig. 1(b). The air mass passes Hof approximately at 14

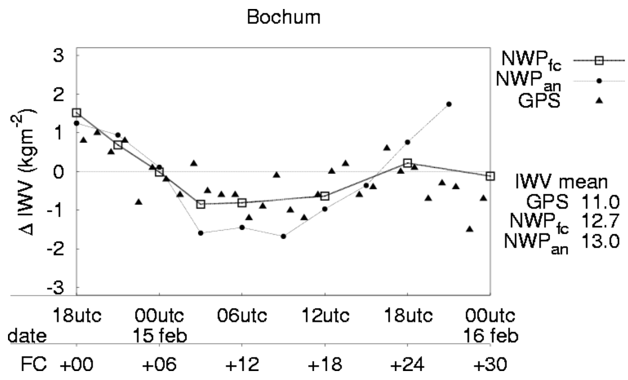


Figure 4. Offset from the mean IWV at forecast times for the time series from GPS NWP-an and NWP-fc for the GPS site Bochum. The values are shown in the lower right corner of each sub-panel. On the second horizontal axis the forecast length is denoted.

February 18utc, Wurzburg at 15 February 00utc and Trier at 15 February 06utc.

The offsets from the mean IWV at forecast time for the three sites and three time series are shown in Fig. 5-7. All NWP IWV values are derived at the receiver location.

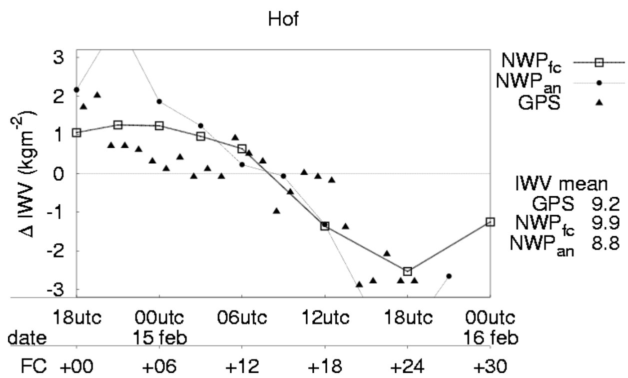


Figure 5. Offset from the mean IWV at forecast times for the time series from GPS NWP-an and NWP-fc for the GPS sites Hof. The values are shown in the lower right corner of each sub-panel

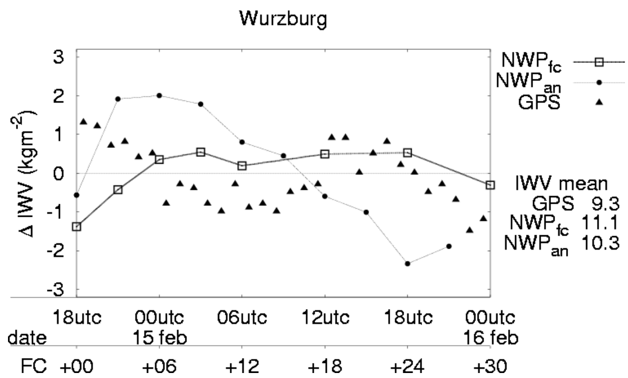


Figure 6. Offset from the mean IWV at forecast times for the time series from GPS NWP-an and NWP-fc for the GPS site Wurzburg. The values are shown in the lower right corner of each sub-panel

The GPS ΔIWV observed in Hof is comparable to the offset observed by the forecast and analysis model apart from the two extreme values of ΔIWV from the analysis model at 14 February 21utc and 15 February 18utc.

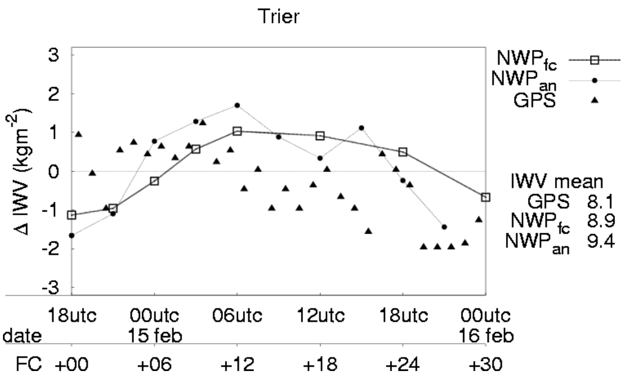


Figure 7. Offset from the mean IWV at forecast times for the time series from GPS NWP-an and NWP-fc for the GPS site Trier. The values are shown in the lower right corner of each sub-panel

For each of the sites Wurzburg and Trier (Fig. 6 and 7) the signals differ a lot. The offset signals for Wurzburg show discrepancies between all three time series during the whole forecast period. The location Trier shows a large difference between GPS ΔIWV and the NWP-fc ΔIWV. The analysis and forecast model have nearly the same curve for this site.

At +00 the offsets ΔIWV from the mean IWV at Hof are nearly equal for all three types of IWV observation. For Wurzburg, a decreasing trend in the GPS ΔIWV is observed at +06, while the NWP-fc ΔIWV increases and NWP-an ΔIWV is constant at this time. At +12, when the air mass of the trajectory is near Trier the GPS ΔIWV decreases. The NWP-fc ΔIWV is becoming constant while the NWP-an ΔIWV is decreasing 3 hours later than +12. Moreover, GPS ΔIWV of Trier at +12 is small, while NWP-fc and NWP-an have positive ΔIWV values.

For the sites Wurzburg and Trier differences are observed in the trend of the IWV offset between GPS IWV and NWP IWV (both forecast and analysis). The differences indicate that the model is wet compared to the GPS IWV estimates.

The ΔIWV values along the trajectory for NWP-fc and NWP-an are shown in Figure 8. The mean IWV at forecast time for the model is calculated at the positions given on the bottom axis. Also shown in this figure are the GPS ΔIWV for the GPS sites Hof, Wurzburg and Trier at forecast times of respectively +00, +06 and +12. as indicated on the middle axis. The GPS locations are not exactly on the trajectory, which results in a small change in ΔIWV derived from NWP with respect to the previous figures where the NWP IWV values where exactly at the receiver locations.

Figure 8 shows that GPS ΔIWV along the trajectory decreases more than both ΔIWV NWP-fc and NWP-an in the period for which we have GPS observations. This may imply that the air mass of the model travelling from around Hof to De Bilt contains more integrated water vapour than would have been expected from the GPS observations.

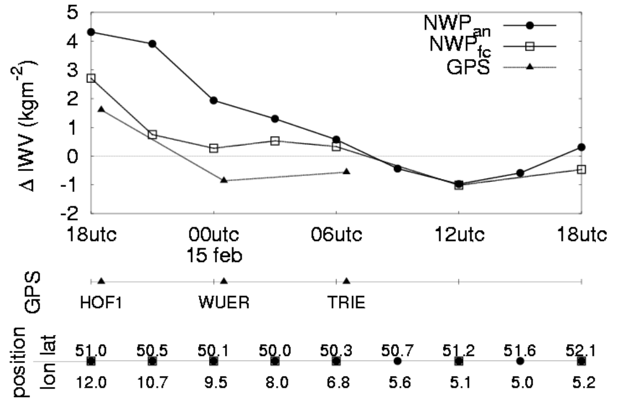


Figure 8. The IWV offset from the mean at forecast time along the +24 trajectory.

5 Conclusions

Above a case is described for which the HIRLAM forecast underestimated the 2-meter temperature in De Bilt more than would have been expected based on the knowledge about necessary model corrections only. GPS Integrated Water Vapour observations are used to examine the changes of IWV amounts and are compared to the IWV derived from the model analysis and forecast. Both systems have biases and errors. To eliminate biases between the model and the GPS observations offsets from the mean IWV value at forecast times are used in the analysis. The trend in NWP derived IWV, forecast and analysis, is compared to the trend in GPS IWV.

At least part of the error in the forecasted 2-meter temperature can be explained by the fact that the air mass according to the model arriving at 18utc on February 15 is too humid with respect to the observed GPS IWV values along the trajectory. A large proportion of the energy from the sun, it was a sunny day, is used for evaporation of the (at first) saturated boundary layer. If the model would have been less humid the energy could have been used to heat the air and the result would have been a higher 2-meter temperature forecast.

Amendment of the forecast for the observation that the model was too humid could have led to a better estimate of the maximum temperature on 15 February 2001.

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